

Chiral and angular momentum content of mesons

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First, we overview the present status of the effective chiral restoration in excited hadrons and an alternative explanation of the symmetry observed in the highly excited hadrons. Then we discuss a method how to define and measure in a gauge invariant manner the chiral and angular momentum content of mesons at different resolution scales, including the infrared scale, where mass is generated. We illustrate this method by presenting results on chiral and angular momentum content of ρ and ρ' mesons obtained in dynamical lattice simulations. The chiral symmetry is strongly broken in the $\rho(770)$ and neither the $a_1(1260)$ nor the $h_1(1170)$ can be considered as its chiral partners. Its angular momentum content in the infrared is approximately the 3S_1 partial wave, in agreement with the quark model language. However, in its first excitation, $\rho(1450)$, the chiral symmetry breaking is much weaker and in the infrared this state belongs predominantly to the $(1/2, 1/2)$ chiral representation. This state is dominated in the infrared by the 3D_1 partial wave and cannot be considered as the first radial excitation of the $\rho(770)$ -meson, in contrast to the quark model.

I. PARITY DOUBLING AND HIGHER SYMMETRY SEEN IN HIGHLY EXCITED HADRONS

The spectra of highly excited hadrons, both baryons [1] and mesons [2], reveal almost systematical parity doubling. This parity doubling can be interpreted as an indication of effective chiral and $U(1)_A$ restorations, for reviews see [3]. The effective chiral restoration means that dynamics of chiral symmetry breaking in the vacuum is almost irrelevant to the mass generation of these highly excited hadrons and their mass comes mostly from the chiral invariant dynamics. This is just in contrast to the lowest lying hadrons such as π ,

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ρ or N , where the chiral symmetry breaking in the vacuum is of primary importance for their mass origin. The latter can be seen from the SVZ sum rules [4, 5] and many different microscopical models.

However, there could be other reasons for parity doubling [6–9] and one needs alternative evidences. If the effective chiral restoration is correct, then the highly excited hadrons should have small diagonal axial coupling constants. It is not possible, unfortunately, to measure these quantities experimentally. The effective chiral restoration also predicts that the states with almost restored chiral symmetry should have small decay coupling constants into the ground state and the pion. The decay coupling constants can be obtained from the known decay widths. It turns out that all excited nucleons that have an approximate chiral partner have a very small decay coupling constant $g_{N^*N\pi}$ (as compared to the pion-nucleon coupling constant). In contrast, the $3/2^-, N(1520)$ state, in which case a chiral partner cannot be identified from the spectrum, has a decay coupling that is even larger than the pion-nucleon coupling. One observes a 100% correlation of the spectroscopic patterns with the πN decays as predicted by effective chiral restoration [10].

The observed high lying spectra have higher degeneracy. The states group not only into possible chiral multiplets, but also states with different spins are approximately degenerate. Chiral symmetry cannot connect states with different spins. This means that higher symmetry is observed, that includes chiral $SU(2)_L \times SU(2)_R$ and $U(1)_A$ as subgroups. It is a key question to understand this high symmetry and its dynamical origin. The answer to this question would clarify the origin of confinement and its interconnection with dynamical chiral symmetry breaking, the mass and the angular momentum generation in QCD. It is possible to explain this degeneracy of states with different spins if one assumes a principal quantum number $n + J$ on top of chiral and $U(1)_A$ restorations [11].

If chiral restoration is correct, then there must be chiral partners to mesons with the highest spin states at the bands around 1.7 GeV, 2 GeV and 2.3 GeV, that are presently missing, see Fig. 2 of ref. [3]. Consequently, a key question is whether these states do not exist or they could not be seen due to some kinematical reasons. It turns out that the latter is correct and a centrifugal repulsion in the $\bar{p}p$ incoming wave suppresses *all* missing states as compared to *all* observed ones [12]. There is a weak signal for missing states once a careful analysis is done. Obviously, the missing states should be also searched in other types of experiments. The same centrifugal suppression in the pion-nucleon scattering is present

for *all* missing chiral partners in the nucleon and delta spectra [8].

The alternative explanation of the large degeneracy seen in both nucleon and meson spectra would be existence of the relation $M^2 \sim n + L$, where L is the orbital angular momentum in the state. The total angular momentum J is constructed from the quark spins S and the orbital angular momentum L according to the standard nonrelativistic rules. The parity of the state is connected with L by the standard nonrelativistic relation [7–9]. In such case the parity doubling is accidental and is not related with chiral symmetry in the states. This scenario requires that there must not be parity partners to the highest spin states in every band. Such relation implies that there are three independent conserved angular momenta, L, S, J . If the high lying states behaved non-relativistically and assuming absence of the spin-orbit force, it would be indeed possible to obtain a principal quantum number $n + L$, like in the nonrelativistic Hydrogen atom.

Such a scenario is inconsistent with QCD and can be ruled out on very general grounds. (i) In QCD, that is a highly relativistic quantum field theory, there is only one conserved angular momentum, J . There are no representations of the Poincaré group that would contain the orbital angular momentum L as a good quantum number. (ii) QCD is a renormalizable quantum field theory. The hadron mass is a renormalization group invariant and does not depend on the renormalization scale. At the same time L is not a renormalization group invariant. Then the relation $M^2 \sim L$ cannot exist within QCD.

From the theoretical side, there exists a transparent model that manifestly exhibits effective chiral restoration in hadrons with large J [13, 14]. While this model is a simplification of QCD, it gives the insight into phenomenon. The model is confining, chirally symmetric and provides dynamical breaking of chiral symmetry in the vacuum [15, 16]. The chiral symmetry breaking is important only at small momenta of quarks. But at large J the centrifugal repulsion cuts off the low-momenta components in hadrons and consequently the hadron wave function and its mass are insensitive to the chiral symmetry breaking in the vacuum. The chiral symmetry breaking in the vacuum represents only a tiny perturbation effect: Practically the whole hadron mass comes from the chiral invariant dynamics.

II. THE CHIRAL CONTENT OF MESONS FROM FIRST PRINCIPLES

To resolve the issue one needs direct information about the chiral structure of states, which can be obtained from ab initio lattice simulations. Here we define and reconstruct in dynamical lattice simulations a chiral as well as an angular momentum decomposition of the leading quark-antiquark component of mesons [17, 18].

The variational method [19] represents a tool to study the hadron wave function. One chooses a set of interpolators $\{O_1, O_2, \dots, O_N\}$ with the same quantum numbers as the state of interest and computes the cross-correlation matrix

$$C_{ij}(t) = \langle O_i(t) O_j^\dagger(0) \rangle .$$

If this set is complete and orthogonal with respect to some transformation group, then it allows to define a content of a hadron in terms of representations of this group.

In [2, 3, 20] a classification of all non-exotic quark-antiquark states (interpolators) in the light meson sector with respect to the $SU(2)_L \times SU(2)_R$ and $U(1)_A$ was done. If no explicit excitation of the gluonic field with the non-vacuum quantum numbers is present, this basis is a complete one for a quark-antiquark system and we can define and investigate chiral symmetry breaking in a state. The eigenvectors of the cross-correlation matrix describe the quark-antiquark component of the state in terms of different chiral representations.

For example, when we study the ρ meson and its excitations, two different chiral representations exist that are consistent with the quantum numbers of the ρ -mesons. Assume that chiral symmetry is not broken. Then there are two independent states. The first one is $|(0, 1) \oplus (1, 0); 1 1^{--}\rangle$; it can be created from the vacuum by the standard vector current, $O_V = \bar{q}\gamma^i\vec{\tau}q$. Its chiral partner is the a_1 meson. The other state is $|(1/2, 1/2)_b; 1 1^{--}\rangle$, which can be created by the pseudotensor operator, $O_T = \bar{q}\sigma^{0i}\vec{\tau}q$. The chiral partner is the h_1 meson.

Chiral symmetry breaking in a state implies that the state should in reality be a mixture of both representations. If the state is a superposition of both representations with approximately equal weights, then the chiral symmetry is maximally violated in the state. If, on the contrary, one of the representations strongly dominates over the other representation, one could speak about effective chiral restoration in this state.

Diagonalizing the cross-correlation matrix one can extract energies of subsequent states from the leading exponential decay of each eigenvalue

$$C_{ij}(t) = \langle O_i(t) O_j^\dagger(0) \rangle = \sum_n a_i^{(n)} a_j^{(n)*} e^{-E_n t} .$$

The corresponding eigenvectors give us information about the structure of each state. Namely, the coefficients $a_i^{(n)}$ define the overlap of the physical state $|n\rangle$ with the interpolator O_i , $a_i^{(n)} = \langle 0|O_i|n\rangle$.

While the absolute value of the coupling constant $a_i^{(n)}$ cannot be defined in lattice simulations (because a normalization of the quark fields on the lattice is arbitrary), their ratio for two different operators O_i and for a given state is well defined [17]. Consequently, the ratio of the vector to pseudotensor couplings, $a_V^{(n)}/a_T^{(n)}$, tells us about the chiral symmetry breaking in the states $n = \rho, \rho'$.

III. THE ANGULAR MOMENTUM CONTENT OF MESONS FROM FIRST PRINCIPLES

The chiral representations can be transferred into the $^{2S+1}L_J$ basis, using the unitary transformation [11, 21]

$$\begin{pmatrix} |(0, 1) \oplus (1, 0); 1 \ 1^{--}\rangle \\ |(1/2, 1/2)_b; 1 \ 1^{--}\rangle \end{pmatrix} = U \cdot \begin{pmatrix} |1; {}^3S_1\rangle \\ |1; {}^3D_1\rangle \end{pmatrix}, \quad (1)$$

where U is given by

$$U = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} \\ \sqrt{\frac{1}{3}} & -\sqrt{\frac{2}{3}} \end{pmatrix}. \quad (2)$$

Thus, using the interpolators O_V and O_T for diagonalization of the cross-correlation matrix, we are able also to reconstruct a partial wave content of the leading $\bar{q}q$ Fock component of the ρ -mesons. Note, that it is a manifestly gauge-invariant definition of the angular momentum content of mesons.

IV. SCALE DEPENDENCE OF THE CHIRAL AND ANGULAR MOMENTUM DECOMPOSITIONS

The ratio $a_V^{(n)}/a_T^{(n)}$ as well as a partial wave content of a hadron are not the renormalization group invariant quantities. Hence they manifestly depend on a resolution scale at which we

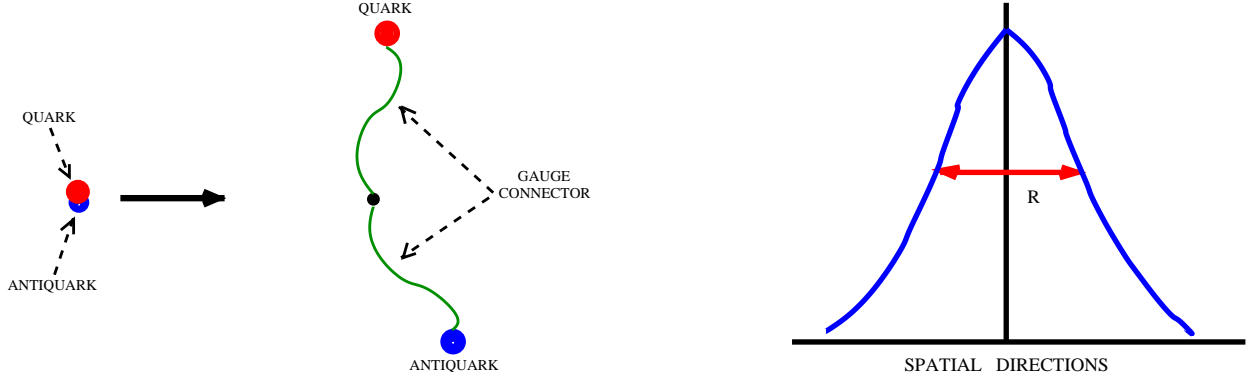


FIG. 1. Gauge-invariant smearing and the resolution scale R definition

probe a hadron. If we probe the hadron structure with the local interpolators, then we study the hadron decomposition at the scale fixed by the lattice spacing a . For a reasonably small a this scale is close to the ultraviolet scale. However, we are interested in the hadron content at the infrared scales, where mass is generated. For this purpose we cannot use a large a , because matching with the continuum QCD will be lost. Given a fixed, reasonably small lattice spacing a a small resolution scale $1/R$ can be achieved by the gauge-invariant smearing of the point-like interpolators. We smear every quark field in spatial directions with the Gaussian profile over the size R in physical units such that $R/a \gg 1$, see Fig. 1. Then even in the continuum limit $a \rightarrow 0$ we probe the hadron content at the resolution scale fixed by R . Such definition of the resolution is similar to the experimental one, where an external probe is sensitive only to quark fields (it is blind to gluonic fields) at a resolution that is determined by the momentum transfer in spatial directions.

V. THE CHIRAL AND ANGULAR MOMENTUM CONTENT OF ρ AND ρ' MESONS

To explore the chiral structure of mesons and possible effective chiral restoration it is important to have a Dirac operator with good chiral properties. We use specifically the Chirally Improved Dirac operator [22]. The set of dynamical configurations is used for two mass-degenerate light sea quarks, see for details ref. [18].

Our cross-correlation matrix is calculated with the following four interpolators

$$O_1 = \bar{u}_n \gamma^i d_n, \quad O_2 = \bar{u}_w \gamma^i d_w, \quad O_3 = \bar{u}_n \gamma^t \gamma^i d_n, \quad O_4 = \bar{u}_w \gamma^t \gamma^i d_w,$$

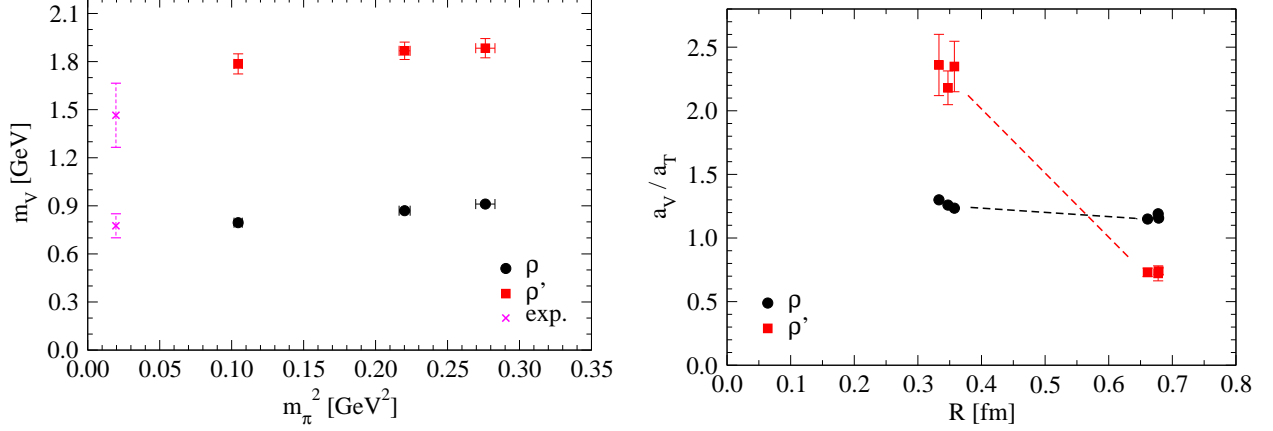


FIG. 2. L.h.s.: The vector meson mass m_V is plotted against m_π^2 . Black circles represent the ground state, ρ , and red squares represent the first excitation, ρ' . The experimental values are depicted as magenta crosses with decay width indicated. R.h.s.: The ratio a_V/a_T is plotted against the smearing width R for all three pion masses. Black circles represent the ground state and red squares the first excitation. Broken lines are drawn only to guide the eye.

where γ^i is one of the spatial Dirac matrices, γ^t is the γ -matrix in (Euclidean) time direction. The subscripts n and w (for narrow and wide) denote the two smearing widths, $R \approx 0.34$ fm and 0.67 fm, respectively. Both the ground state mass and the mass of the first excited state of the ρ -meson are shown on the l.h.s. of Fig. 2.

On the r.h.s. of Fig. 2 we show the R -dependence of the ratio a_V/a_T both for the ground state ρ -meson and its first excited state. For the ground state at the smallest resolution scale of $R \approx 0.67$ fm this ratio is approximately 1.2, i. e., we see a strong mixture of the $(0, 1) \oplus (1, 0)$ and $(1/2, 1/2)_b$ representations in the ρ -meson. Consequently, there is no chiral partner to $\rho(770)$. Such ratio implies that the vector meson in the infrared is approximately a 3S_1 state with a tiny admixture of a 3D_1 wave.

However, the situation changes dramatically for the first excited state, $\rho' = \rho(1450)$. In this case a strong dependence of the ratio on the resolution scale is observed. Although we do not have the precise value of the ratio a_V/a_T for $\rho(1450)$ at large $R \sim 0.8 - 1$ fm, it is indicative that this value is very small. One observes a significant contribution from the $(1/2, 1/2)_b$ representation and a contribution of the other representation is suppressed. This indicates a smooth onset of effective chiral restoration. The approximate chiral partner is $h_1(1380)$. This small ratio also implies a leading contribution of the 3D_1 wave. This result is

inconsistent with ρ' to be a radial excitation of the ground state ρ -meson, i. e., a 3S_1 state, as predicted by the quark model.

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